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REPORT OF INVESTIGATIONS/1992

Machining of Fe_3Al Intermetallics

By Jack R. Woodyard

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

at. %	atomic percent	in/min	inch per minute
°C	degree Celsius	lb	pound
cm	centimeter	mm	millimeter
cm/min	centimeter per minute	μm	micrometer
c/sec	cycle per second	scmps	surface centimeter per second
g	gram	sfpm	surface foot per minute
in	inch		

MACHINING OF Fe_3Al INTERMETALLICS

By Jack R. Woodyard[1]

ABSTRACT

Scientists at the U.S. Bureau of Mines are studying iron aluminides as possible substitutes for stainless steels to reduce the Nation's dependence on imported strategic and critical materials. In a Bureau investigation on the mechanical properties of Fe-28Al, it was found that the material's machining properties were significantly improved at slow tool and feed speeds. Machining techniques normally used for brittle materials failed or were costly. Further experiments using a 5-in (12.7-cm) mill cutter with carbide inserts, operating dry at minimum machining speeds, produced visually smooth sample surfaces with no tool damage. As a result of these experiments and a review of published data on hydrogen embrittlement of iron aluminide under tension, non-water-based (e.g., sulfur-based) lubricants were chosen for production machining. Four-flute, 3/4-in (19-mm) carbide end mills were used at slow speed under lubrication. This latter procedure reduced tool wear and breakage by a factor of 2. Machined surfaces and specimen cross sections were analyzed by scanning electron microscopy to detect microcracking. Tensile tests gave the expected yield and ultimate strengths, indicating that no degradation by low-speed machining occurred. This study extends this work to show that the alloy can be machined at higher speeds using high-speed steel end mills, and that water-soluble cutting oil is a suitable lubricant and coolant.

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INTRODUCTION

Scientists at the U.S. Bureau of Mines are studying iron aluminides because of their high strength, low density, and extreme corrosion resistance to oxidizing and sulfidizing environments. Made from low-cost, readily available components (iron and aluminum), these intermetallics could, if substituted for stainless steels, reduce the Nation's dependence on imported strategic and critical materials.

Iron aluminides near the composition Fe-25Al[2] are poorly malleable at room temperature, form large grains upon casting, and show room temperature brittleness under tension. Room temperature brittleness has been shown to be due to a tension-catalyzed reaction with water vapor. Since milling loads the work piece in compression, not tension, and the temperature at the cutting interface is high, environmental embrittlement is not considered to be a problem in this study. During machining, iron aluminides are resistant to grinding; they tend to shatter tungsten carbide tools at conventional machining speeds and to embrittle in processes such as electron discharge machining.

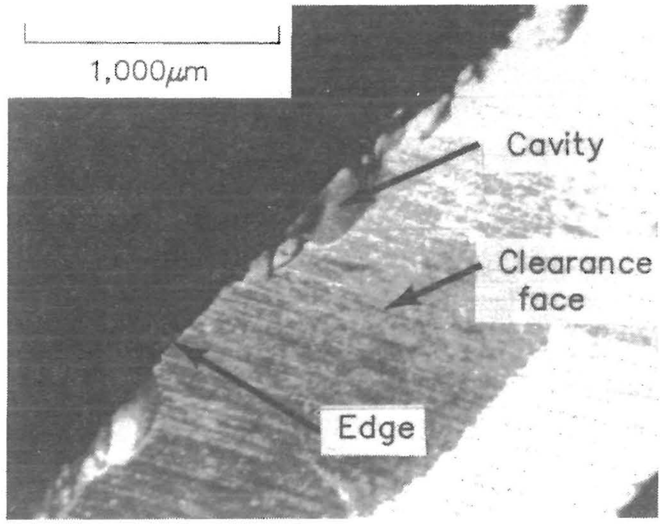

Figure 1.—Failed tungsten carbide end mill.

In 1961, a study found that these alloys tended to work harden and required sharp tools and slow machining speeds.[3] "Slow" machining speeds were not defined, but could be expected to be near the lowest settings available on the machine. Little else has been published on machining since then.

In previous work, while attempting to produce tensile specimens from 0.1-in (25-mm)-thick, rolled Fe-28Al plates, Bureau machinists observed that the alloy shattered carbide insert end mills upon contact at operating speeds greater than 1,000 sfpm (80 scmps). They also observed that high-speed grinding caused a loss of one part grinding wheel for each two parts alloy removed; however, operation of a shaper mill with a carbide-tipped tool, at the slow speed of approximately 1 c/sec produced satisfactory surface finishes with smooth chip production. With this information, tensile bars were machined at 24.54 sfpm (12.5 scmps) using carbide end mills lubricated with cutting oil, but the tools failed quickly and exhibited large cavities in the cutting edge (fig. 1), showing the strong tendency of carbide tools to pressure weld to iron-based alloys at slow machining speeds.

Before these intermetallics can be widely used, their machinability must be demonstrated. The purpose of this paper is to show that high-speed steel end mills can be used to machine Fe-28Al, and to provide information for the production of laboratory samples used for material property studies.

ACKNOWLEDGMENTS

The author would like to thank J. C. Rawers, R. D. Wilson, K. K. Schrems, W. K. Collins, and T. A. Alder, Albany Research Center, and V. K. Sikka, Oak Ridge National Laboratory, Oak Ridge, TN, for numerous consultations, and J. Lamp and Z. Huston, Albany Research Center, for special work in the machine shop.

EXPERIMENTAL PROCEDURES

Binary Fe-28Al castings were prepared by melting and pouring in a vacuum induction furnace as recommended in the literature.[4] Iron and aluminum used for the heats were 99.9% pure. Each 3.3-lb (1,500-g) heat was cast in

[2]Compositions are shown in atomic percent.

[3]Battelle Memorial Institute (Columbus, OH). Review of Developments in Iron-Aluminum-Base Alloys (Def. Met. Inf. Cent. contract AF33(616)-7747). Def. Met. Inf. Cent. Memo. 82, Jan. 30, 1961, 60 pp.; NTIS (OTS) PB 161232.

[4]Sikka, V. K. Melting of Iron Aluminide Alloys. Proceedings of Fossil Energy Minerals Conference (Oak Ridge, TN, May 15-17, 1990). Oak Ridge Natl. Lab., 1990, p. 219.

a preheated graphite mold treated with zirconia mold wash. Resulting castings were approximately 1 in (25 mm) thick.

Each casting was hot rolled with approximately 15% reduction per pass according to a schedule recommended by Sikka:[5]

From starting size down to 0.25 in (6 mm)	1000° C
From 0.25 in (6 mm) down to 0.20 in (5 mm)	800° C
From 0.20 in (5 mm) down to 0.10 in (2.5 mm)	650° C

The resulting plates were used to make 0.10-in (2.5-mm)-thick, 4.2-in (110-mm)-wide machining specimens.

All machining studies were done with a Kearney & Trecher[6] horizontal milling machine with vertical mill head attachment. Since it is known that these alloys can be machined at slow speeds, the tests started at a slow speed and progressed to higher speeds. Starting at 2.95 sfpm (1.50 scmps), the width of the specimen was machined to a depth of 0.100 in (2.54 mm). Upon completion of the cut, the machined face of the work piece, the affected portion of the tool, and samples of the chips were removed and stored for inspection. With a fresh work piece face and a fresh tool surface, the cutting speed was advanced and another cut was made. This procedure was repeated until the tool failed while cutting. Tool failure was apparent through a visible degradation of the surface finish on the work piece or noticeable dulling or roughening of the tool's cutting edge(s). This final cutting speed, below which good cuts are made, was logged as the *failure speed*. Failure speed was determined for both steel and carbide, four-flute, 3/4-in (19-mm)-diameter end mills.[7] Depth of cut was established at 0.100 in (2.54 mm). Cutter speed and feed rate were varied under the constraint of maintaining a chip load per tooth, the theoretical chip thickness, as close to 0.005 in (0.127 mm) as possible. The depth of cut and chip load were established arbitrarily based on the experience of the machinist.

To study the effects of cutting fluids, failure speed studies were made with steel tools for each of three conditions: (1) cut dry, (2) cut with Mobile Gamma Oil (cutting oil) (66552 5) painted on the tool and work piece during milling, referred to hereafter as oil, and (3) cut with tool and work piece flooded with a 7% solution of Chevron Soluble Oil, referred to hereafter as water.

Water, oil, and air have specific heats roughly in the ratio 4:2:1. Thus, tests run with oil indicate the importance of lubrication on the machining process, while tests run with water indicate the importance of cooling.

Chip ratios, the ratio of the theoretical chip thickness to the measured chip thickness, as a function of cutter speed were used to indicate the amount of energy lost to chip thickening, to determine a relative cutting efficiency. These arbitrarily defined chip ratios were determined from the average of six thickness measurements of randomly sampled chips from a given cutting. Thickness measurements were made with a micrometer at the approximate geometrical center of the chip as a matter of convenience. This value was divided into the theoretical chip thickness (chip load per tooth) to give the *chip ratio*. Higher chip ratios indicated more efficient cutting. This value could be expected to peak as a function of cutting speed to indicate the most desirable machining conditions.

Some preliminary tests were run to indicate (1) tool life, measured as the number of times the sample could be milled with the same end mill; (2) the effects of increasing the chip load per tooth; (3) the effects of small chromium additions to the alloy; and (4) the effects of high-revolution-per-minute cutting (table 1).

RESULTS AND DISCUSSION

Machined surfaces appeared bright and shiny visually and were smooth to the touch for all work pieces machined below failure speed. Photomicrographs from the scanning electron microscope showed ductile smearing on the machined surface of a specimen that was dry cut (fig. 2), but clean cutting was observed on the upstroke face of a cut in progress (fig. 3), indicating problems with tool geometry or cutting temperature effects. At the end of the cutting, brittle fracture was occasionally seen (fig. 4). No cracks were observed over the main surface of the work piece.

Tool samples were free of visual and tactile damage for speeds below failure speed. Spent steel mill heads exhibited ductile wear causing the cutting edges to round and surfaces to smear (fig. 5). Steel mill heads rarely exhibited chipping. At some points work piece material was welded to the worn edges or in the chipped pockets of the steel end mills. The lack of chipping indicated that the material tended to temperature weld rather than pressure weld to the rake of the tool.[8] (Compare figures 1 and 5.)

[5]Sikka, V. K. (Oak Ridge Natl. Lab.). Private communication, 1990; available upon request from J. R. Woodyard, BuMines, Albany, OR.

[6]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

[7]Steel mills were Putman HS 3/4 in, EDP-94069; carbide mills were Metal Remover, 3/4 in, No. 155-8253-47, cobalt binder.

[8]Shaw, M. C. Metal Cutting Principles. MIT Press, 3d. ed., 1960, pp. 11.15-11.18.

Table 1.—Milling machine study, Fe-28Al

(Kearney & Trecher Horizontal Milling Machine with vertical mill head attachment, 3/4-in (19-mm), 4-flute end mill tool; Fe-28Al plus Cr, as rolled, 0.100 in (2.54 cm) thick and 4.210 in (110 mm) wide; rougher cut, stock fed counter to rotation of tool; cut depth 0.100 in (2.54 cm))

Sample no. and type of tool	Revolutions		Cutter speed		Feed rate[1]		Chip load		Chip thickness		Chip ratio[2]	Tool failure[3]
	min	s	sfpm	scmps	in/min	cm/min	in	mm	in	mm		
NO LUBRICATION												
Steel tool:												
0228-1	15	0.25	2.95	1.50	0.3750	0.0159	0.0063	0.159	0.0111	0.2807	0.57	N
0228-2	27	.45	5.30	2.69	.5625	.0238	.0052	.132	.0097	.2451	.54	N
0228-3	50	.83	9.82	4.99	1.1250	.0476	.0056	.143	.0108	.2752	.52	N
0301-1	90	1.50	17.67	8.98	1.8750	.0794	.0052	.132	.0092	.2337	.57	N
0301-2	247	4.12	48.50	24.64	5.2500	.2222	.0053	.135	.0085	.2155	.63	Y
0301-3	165	2.75	32.40	16.46	3.1250	.1323	.0047	.120	.0077	.1960	.61	Y
0301-4/1 ..	136	2.27	26.70	13.57	2.6250	.1111	.0048	.123	.0093	.2366	.52	N
0301-4/2 ..	136	2.27	26.70	13.57	2.6250	.1111	.0048	.123	.0080	.2024	.61	N
0301-4/3 ..	136	2.27	26.70	13.57	2.6250	.1111	.0048	.123	.0074	.1875	.65	N
0301-4/4 ..	136	2.27	26.70	13.57	2.6250	.1111	.0048	.123	.0083	.2096	.58	N
0301-4/5 ..	136	2.27	26.70	13.57	2.6250	.1111	.0048	.123	.0078	.1973	.62	Y
0304-1	136	2.27	26.70	13.57	7.7500	.3281	.0142	.362	.0162	.4102	.88	Y
0304-2	136	2.27	26.70	13.57	5.2500	.2222	.0097	.245	.0124	.3137	.78	Y
Carbide tool:												
0304-3	136	2.27	26.70	13.57	2.6250	.1111	.0048	.123	.0097	.2464	.50	Y
OIL												
Steel tool:												
0306-1	136	2.27	26.70	13.57	2.6250	0.1111	0.0048	0.123	0.0069	0.1744	0.70	N
0306-2	165	2.75	32.40	16.46	3.1250	.1323	.0047	.120	.0061	.1558	.77	N
0306-3	247	4.12	48.50	24.64	5.2500	.2222	.0053	.135	.0069	.1740	.78	Y
Carbide tool:												
tensile[4] ...	125	2.08	24.54	12.47	1.0000	.0423	.0020	.051	NAp	NAp	([5])	N
WATER												
Steel tool:												
0307-1	136	2.27	26.70	13.57	2.6250	0.1111	0.0048	0.123	0.0085	0.2155	0.57	N
0307-2	202	3.37	39.66	20.15	3.7500	.1587	.0046	.118	.0064	.1621	.73	N
0307-3	247	4.12	48.50	24.64	5.2500	.2222	.0053	.135	.0075	.1905	.71	N
0307-4	302	5.03	59.30	30.12	6.3750	.2699	.0053	.134	.0057	.1435	.93	N
0307-5	360	6.00	70.69	35.91	7.7500	.3281	.0054	.137	.0068	.1736	.79	B
0307-6[6] ...	302	5.03	59.30	30.12	6.3750	.2699	.0053	.134	.0048	.1223	1.10	Y
0307-7[7] ...	302	5.03	59.30	30.12	6.3750	.2699	.0053	.134	.0074	.1888	.71	B
Carbide tool:												
0307-8[7] ...	1000	16.67	196.35	99.75	18.5000	.7832	.0046	.117	NAp	NAp	([8])	B

NAp Not applicable.
[1]Feed rate adjusted to keep chip load near 0.005 in (0.127 mm).
[2]Chip ratio = theroretical chip thickness/measured chip thickness.
[3]Y = yes; N = no; B = tool failed upon contact, cutting surfaces burned.
[4]Cr content = 0.00, 0.46, or 2.01 at. %.
[5]Tensile bars milled; average of 10 bars per tool before tool failure.
[6]Cr content = 0.46 at. %.
[7]Cr content = 2.01 at. %.
[8]High-speed test—immediate tool destruction.

Chips were uniform and uncolored except for passes made at failure speed. At failure speed the chips became yellowed. Chips recovered from milling were uniformly tapered from the start of cutting through to the point of complete removal from the work piece (fig. 6). The leading edge of the chip was the thinnest portion of the chip. Tearing or cracking was evident on the leading edge, and visual evidence of oxide spalling was found on the side near the trailing edge (fig. 7). The face of the chip (portion in contact with the tool) showed ductile smearing near the leading edge, but smooth cutting was evident in the body of the chip, compatible with the ductile smearing on the work piece finish and clean cutting on the upstroke face. The back of the chip showed sharp, plate-like serrations perpendicular to the chip length (fig. 8). In longitudinal cross section, shear bands are evident and define the serrations seen on the chip back (fig. 9), but

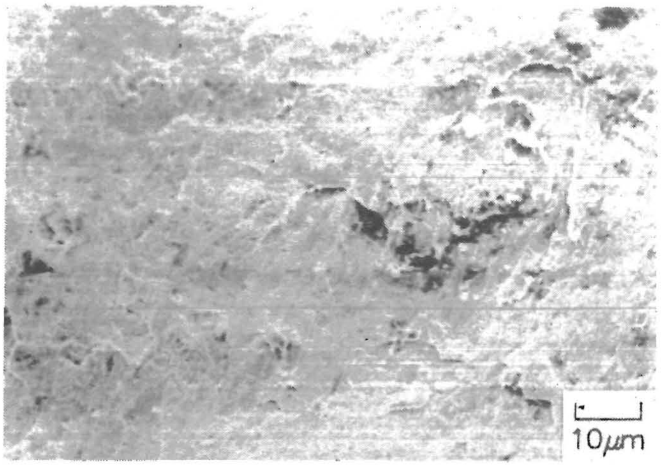

Figure 2.—Ductile smearing on machined face of specimen, dry cut, 13.6 scmps.

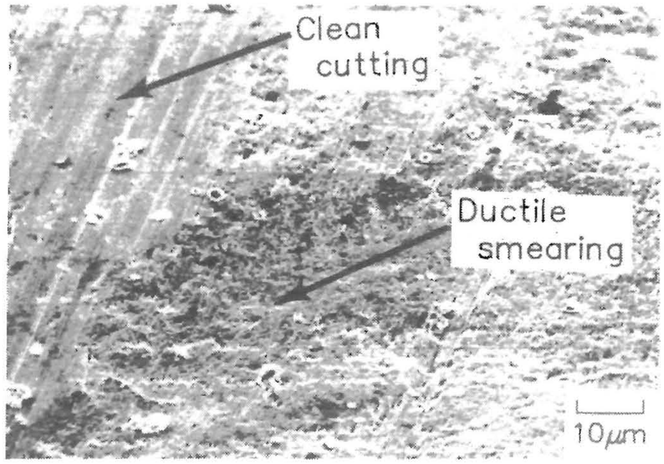

Figure 3.—Clean cutting alongside ductile smearing observed on upstroke face, dry cut, 13.6 scmps.

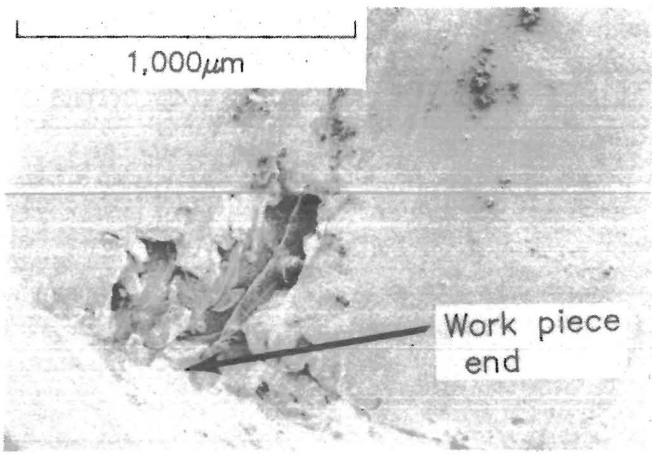

Figure 4.—Brittle fracture at end of machining pass on machined face of specimen, dry cut, 13.6 scmps.

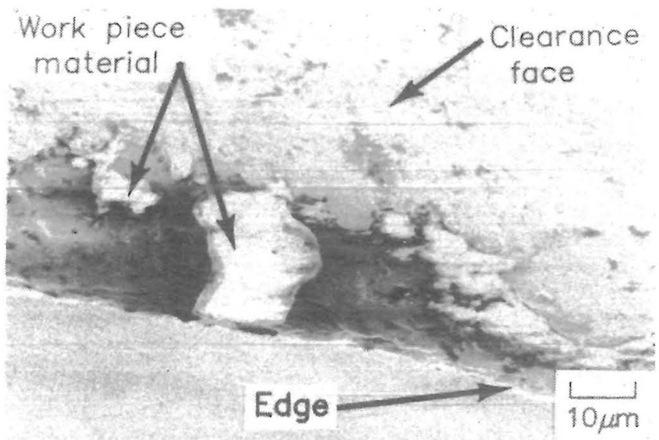

Figure 5.—Failed high-speed steel end mill. Note material welded to edge of tool.

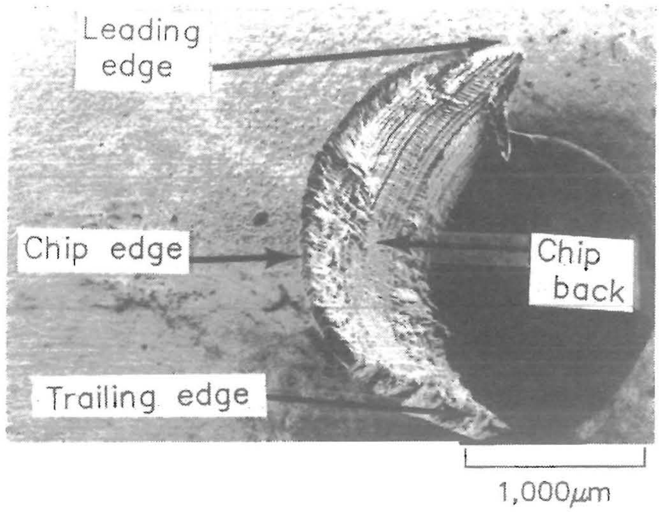

Figure 6.—Machining chip. Thin, pointed tip is focus of cut initiation. Broad, flat end is point at which cutting edge left work piece. Note taper from chip beginning to chip ending.

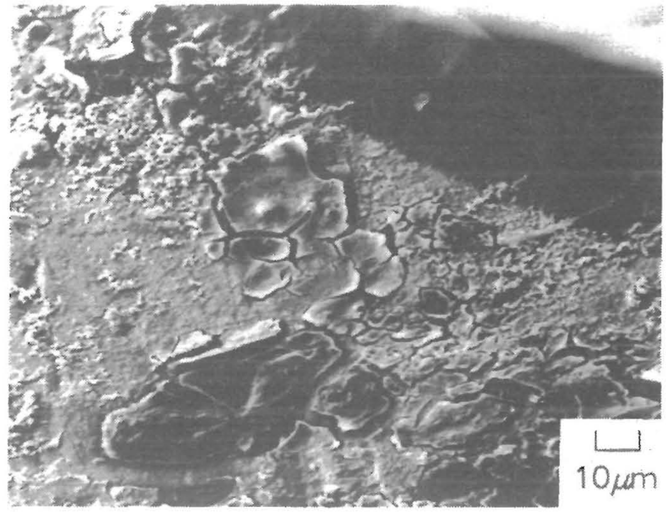

Figure 7.—Oxide spalling on chip side, near trailing edge of chip.

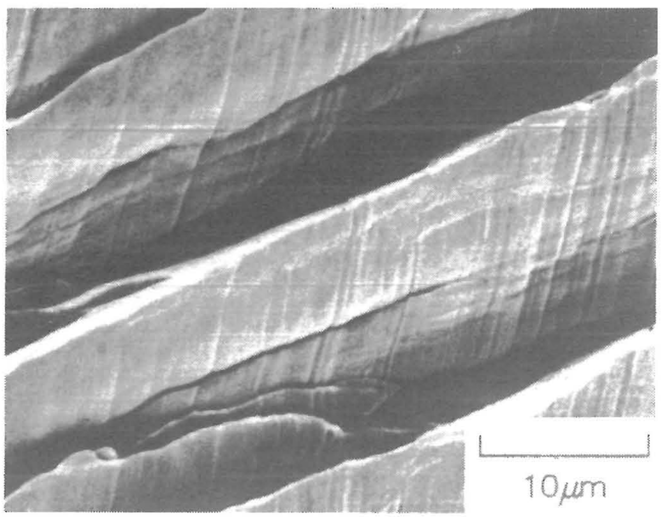

Figure 8.—Heavy striations on chip back.

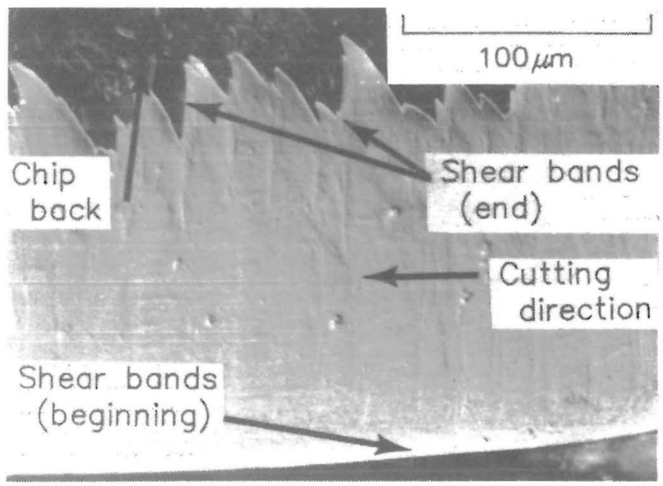

Figure 9.—Shear bands through longitudinal cross section of chip. Note lack of cracking in chip body and ductile smearing of shear bands at chip face.

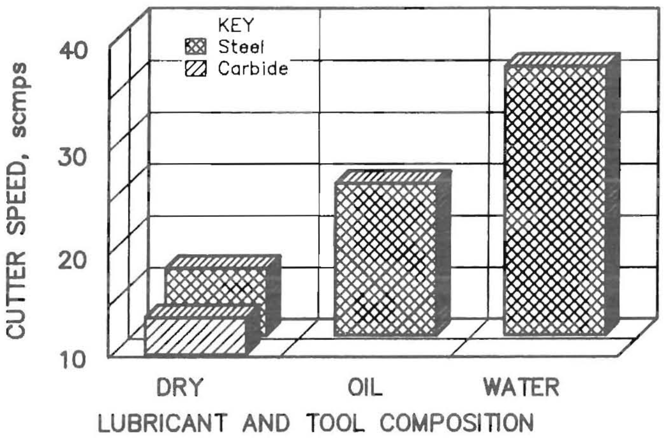

Figure 10.—Failure speed as function of lubrication environment.

there are no signs of cracking through the body of the chip. The lack of cracking indicates that this material cut in a ductile manner.

Steel end mills allowed higher machining speeds than carbide end mills (fig. 10 and table 1), and lubrication or cooling of the work area increased the allowable machining speeds for both tool materials. A water flood was more effective than oil painted on the surface, indicating that cutting temperature effects dominated lubrication effects.

Chip ratios showed little correlation with cutting speed except with the samples flooded with water (fig. 11). Potential peak values were overshadowed by statistical variations between chips, but the chip ratio at failure speed increased with cutting fluid use. The performance increase of water over oil indicated that cooling effects were more important than lubricating effects.

Preliminary tests (table 1) showed: (1) tool life (samples 0301-4/1 through 0301-4/5 and the tensile bars) can be expected to be short, particularly at speeds near the failure speed; (2) increasing the chip load per tooth (samples 0304-1 and 0304-2) has detrimental effects; (3) adding chromium (samples 0307-6 and 0307-7) has detrimental effects; (4) even with water flood, machining speeds normally used for iron-based alloys (sample 0307-8) are detrimental.

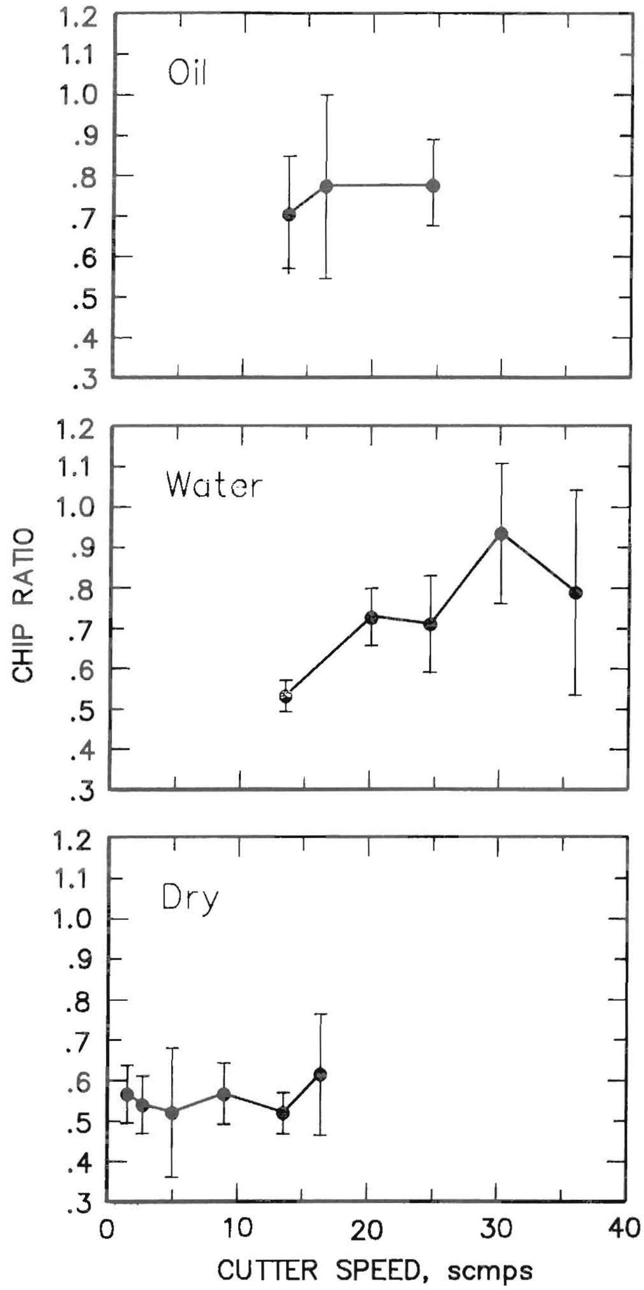

Figure 11.—Chip ratio as function of cutter speed for three lubrication environments.

CONCLUSIONS

- Fe-28Al plates can be machined at speeds less than 70 sfpm (35 scmps) using high-speed tool steel.
- Steel end mills allowed higher machining speeds than carbide end mills for comparable cutting environments.
- Cutting temperature effects dominate lubrication effects at these machining speeds.

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